Nocturnal Boundary Layer Effects on Sound Propagation

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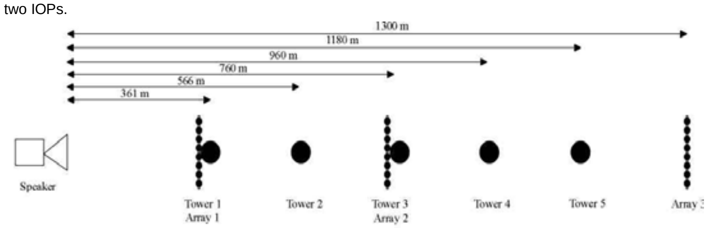
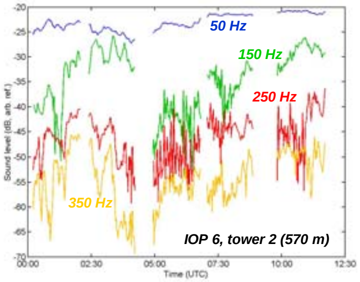
Abstract

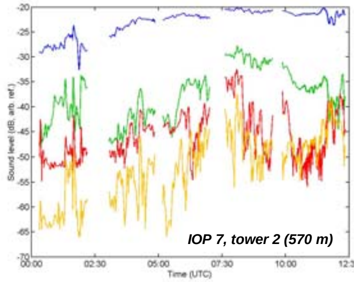
Fair weather, nighttime conditions are often viewed as benign for sound propagation. In this paper, some recent experimental results that contradict this view are discussed. The measurements were performed in conjunction with the Cooperative Atmospheric-Surface Exchange Study (CASES-99), an ambitious field study whose purpose was to characterize the evolution and structure of the nighttime atmospheric boundary layer during fair weather. Conducted in Kansas, U.S.A. during October 1999, CASES-99 included extensive, state-of-the-art meteorological instrumentation. The concurrent ARL acoustical experiment involved a series of five 6-m towers placed at distances between 300 and 1200 m from a loudspeaker. Each tower had microphones at heights of 0.5, 1, 2, and 3 m. Signal behavior on two nights (13 and 17 October 1999) has been analyzed particularly closely. The evolution of the received acoustic signal energy was determined on these nights by a complicated combination of gradual strengthening of the nocturnal inversion, strong discrete local weather phenomena (likely density currents and solitary waves), and signal variations attributable to shifting interference patterns in the propagating acoustic modes. Substantial signal variability, including fading episodes of more than 15 dB and lasting several minutes, was observed.

Description of the Experiment

A low-frequency loudspeaker was positioned roughly 1.8 km southwest of the main 60-m tower. The sound transmission path ran due north of the speaker over gently sloped terrain. A 50-Hz square wave was broadcast. A series of five 6-m towers were placed at distances between 361 and 1180 m from the source, as shown below. Each tower had microphones at heights of 0.5, 1, 2, and 3 m. The microphone signals were sampled at 12 kHz and recorded onto digital audio tape. FFT processing was used to separate the harmonics. For IOPs 6 and 7, tapes were exchanged regularly throughout the night, providing a nearly continuous record of the sound level from sunset until sunrise. In this paper, we focus on these two IOPs.





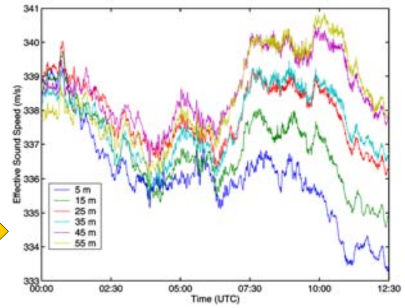


Conclusions

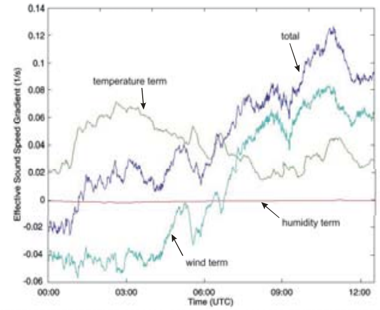
- Acoustical measurements during CASES-99 have provided unique insights into the characteristics of propagation in the nocturnal boundary layer (NBL). Sound levels are much more active than previously thought. Fading/enhancement episodes of 10 to 20 dB, lasting several minutes to an hour, were frequently observed.
- Discrete events, such as density currents and gravity waves, have observable effects on acoustical signals, although substantial variability in sound levels occurs outside such events.
- Data from a tall tower can be used predict variations in sound levels in the NBL with good success at 50 Hz, but less so at 150 Hz. Tethersonde data are too infrequent to capture these variations.
- Sensitivity of sound waves to changes in NBL structure suggests possibilities for new remote sensing techniques, such as travel-time or modally based tomography.

Dependence of Propagation on the Effective Sound Speed

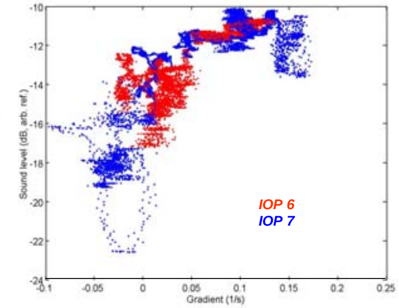
For nominally horizontal propagation, sound refracts downward (creating a surface duct) for a positive gradient in the effective sound speed profile, and refracts upward for a negative gradient. The effective sound speed is defined as the actual sound speed plus the component of the wind velocity in the direction of propagation. In our experiment, $c_{eff} = c + v$, where c is the sound speed and v is the northward wind component. The sound speed is given by $c = \sqrt{\gamma_d R_d T(1+0.51r)}$, where T is temperature and r the water vapor mixing ratio. A bulk approximation to the effective sound speed gradient was made showing the contributions from the wind, temperature, and humidity below. We see that the trend toward an increasingly positive gradient is due primarily to a shifting of the wind direction.



Effective sound speed at 6 heights on the 60-m tower, IOP 6. At sunset, gradient is negative due to upwind propagation. By sunrise, propagation is downwind and a deep temperature inversion has formed, creating a strong positive gradient.



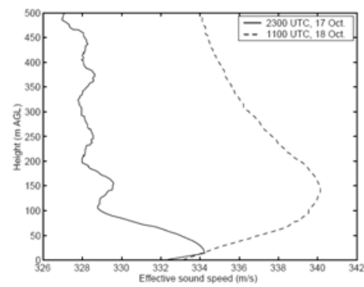
Bulk effective sound speed gradient and contributions from temperature, humidity, and wind during IOP 6.



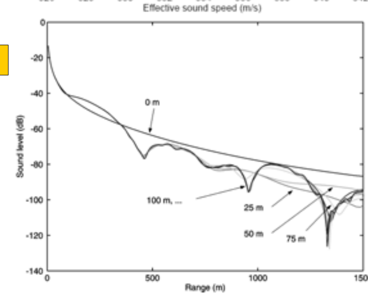
Scatter plot of the sound level at 50 Hz (tower 2) vs. the effective sound-speed gradient. (Gradient approximated by difference between 5 m and 55 m levels on tower.)

Results and Propagation Modeling in IOP 7

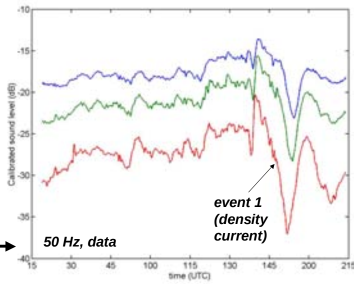
It is unclear *a priori* whether the 60 m tower and tethersonde provide profiles high enough into the atmosphere to model the sound propagation well. To address the limiting height issue, we consider a test based on truncating the rawinsonde data at various heights and using the truncated profiles as input to a parabolic equation (PE) model. The truncation height is moved from 0 m AGL up to 500 m in 25 m increments. The figure below shows by 75 m to 100 m the solution converges to a single result. This means that the tethersonde sufficiently covers the altitudes of the atmosphere important in the experiment while the 60 m tower data is marginally sufficient. Atmospheric data from the 60-m tower and ANL tethersonde were used as input to a parabolic equation (PE) code, which calculates the propagation of sound based on a narrow-angle (one-way) approximation to the full wave equation. A finite-impedance lower BC controls the partial ground reflection. Calculations were performed for two-hour period including a density current event observed during IOP 7. To create time-dependent calculations from the tower data, we assumed that the events had a fixed spatial structure and infinite spatial extent perpendicular to their direction of translation as they moved across the CASES-99 site.



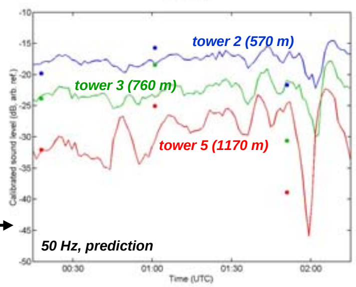
Effective sound speed profiles for the two cases used in a sensitivity test of the sound propagation predictions to the height of profile truncation.



Sound level predictions at 150 Hz for the rawinsonde launch at 2300 UTC on 17 Oct. The height the atmospheric profile was truncated is indicated on the figure.



Sound levels at towers 2, 3, and 5 over a two hour period including Event 1 (density current).



Modeled sound level at 50 Hz for the 2 hr period of IOP 7 including event 1. Lines represent predictions from the main tower data and circles from the tethersonde data.